7.9.6 Application

Application of the relationship in Equation 7.36 is limited to uniform or gradually varying flow conditions that are in straight or mildly curving channel reaches of relatively uniform cross section. However, design needs dictate that the relationship also be applicable in nonuniform, rapidly varying flow conditions often exhibited in natural channels with sharp bends and steep slopes, and in the vicinity of bridge piers and abutments.

To fill the need for a design relationship that can be applied at sharp bends and on steep slopes in natural channels, and at bridge abutments, it is recommended that Equation 7.36 be used with appropriate adjustments in velocity and/or stability factor as outlined in the following sections.

Wave Erosion

Waves generated by wind or boat traffic have also been observed to cause bank erosion on inland waterways. The most widely used measure of riprap's resistance to wave is that developed by R. Y. Hudson "Laboratory Investigations of Rubble-Mound Breakwaters," 1959. The so-called Hudson relationship is given by the following equation:

$$W_{50} = (\gamma_s H^3) / (2.20 [S_s - 1]^3 \cot \theta) \qquad \textbf{(7.40)}$$

Where: W_{50} = weight of the median particle, kg (lb)
γ_s = unit weight of riprap (solid) material, kg/m^3 (lb/ft^3)
H = the wave height, m (ft)
S_s = specific gravity of riprap material
θ = bank angle with the horizontal

Assuming:

$S_s = 2.65$ and $\gamma_s = 2643$ kg/m^3 (165 lb/ft^3), Equation 7.40 can be reduced to:

$$W_{50} = 267.4\, H^3/\cot \theta \qquad (W_{50} = 16.7\, H^3/\cot \theta) \qquad \textbf{(7.41)}$$

In terms of an equivalent diameter Equation 7.41 can be reduced to:

$$D_{50} = 0.57H/\cot^{1/3} \theta \qquad (D_{50} = 0.75H/\cot^{1/3} \theta) \qquad \textbf{(7.42)}$$

Where: D_{50} = median riprap size, m

Methods for estimating a design wave height are presented in Appendix A of this chapter. Equation 7.42 is presented in nomograph form in Figure 7-29. Equations 7.41 and 7.42 can be used for preliminary or final design when H is less than 1.5 m (5 ft), and there is no major overtopping of the embankment.

7.9.7 Steep Slopes

Flow conditions in steep sloped channels are rarely uniform, and are characterized by high flow velocities and significant flow turbulence. In applying Equation 7.36 to steep slope channels, care must be exercised in the determination of an appropriate velocity. When determining the flow velocity in steep sloped channels, it is recommended that Equation 7.43 be used to determine the channel roughness coefficient. It is also important to thoughtfully consider the guidelines for selection of stability factors as presented in Table 7.8.

On high gradient streams it is extremely difficult to obtain a good estimate of the median bed material size. For high gradient streams with slopes greater then 0.002 m/m (ft/ft) and bed material larger than 0.06 m (0.2 ft) (gravel, cobble, or boulder size material), it is recommended that the relationship given in the following equation be used to evaluate the base Manning's n.

$$\mathbf{n = 0.32\, S_f^{0.38}\, R^{-0.16} \qquad (n = 0.39\, S_f^{0.38}\, R^{-0.16}) \qquad (7.43)}$$

Where: S_f = friction slope, m/m (ft/ft)
R = hydraulic radius, m (ft)

7.9.8 Bridge Piers

For recommendations, see Chapter 9, Bridges.

7.9.9 Ice Damage

Ice can affect riprap linings in a number of ways. Moving surface ice can cause crushing and bending forces as well as large impact loadings. The tangential flow of ice along a riprap lined channel bank can also cause excessive shearing forces. Quantitative criteria for evaluating the impact ice has on channel protection schemes are unavailable. However, historic observations of ice flows in New England rivers indicate that riprap sized to resist design flow events will also resist ice forces.

For design, consideration of ice forces should be evaluated on a case by case basis. In most instances, ice flows are not of sufficient magnitude to warrant detailed analysis. Where ice flows have historically caused problems, a stability factor of 1.2 to 1.5 should be used to increase the design rock size. Please note that the selection of an appropriate stability factor to account for ice generated erosive problems should be based on local experience.

7.9.10 Rock Gradation

The gradation of stones in riprap revetment affects the riprap’s resistance to erosion. The stone should be reasonably well graded throughout the riprap layer thickness. Table 7-9 presents the median particle size of three types of riprap which have gradations defined in the ConnDOT standard specifications. All designs should consider using the ConnDOT standard gradations, however if a design requires a non-standard median particle size, then the AASHTO guidelines for rock gradations as presented in HEC-11 should be used.

Table 7-9 D_{50} of Available Riprap

Riprap Type	D_{50} mm
Modified	125 (5 inches)
Intermediate	200 (8 inches)
Standard	380 (15 inches)

7.9.11 Layer Thickness

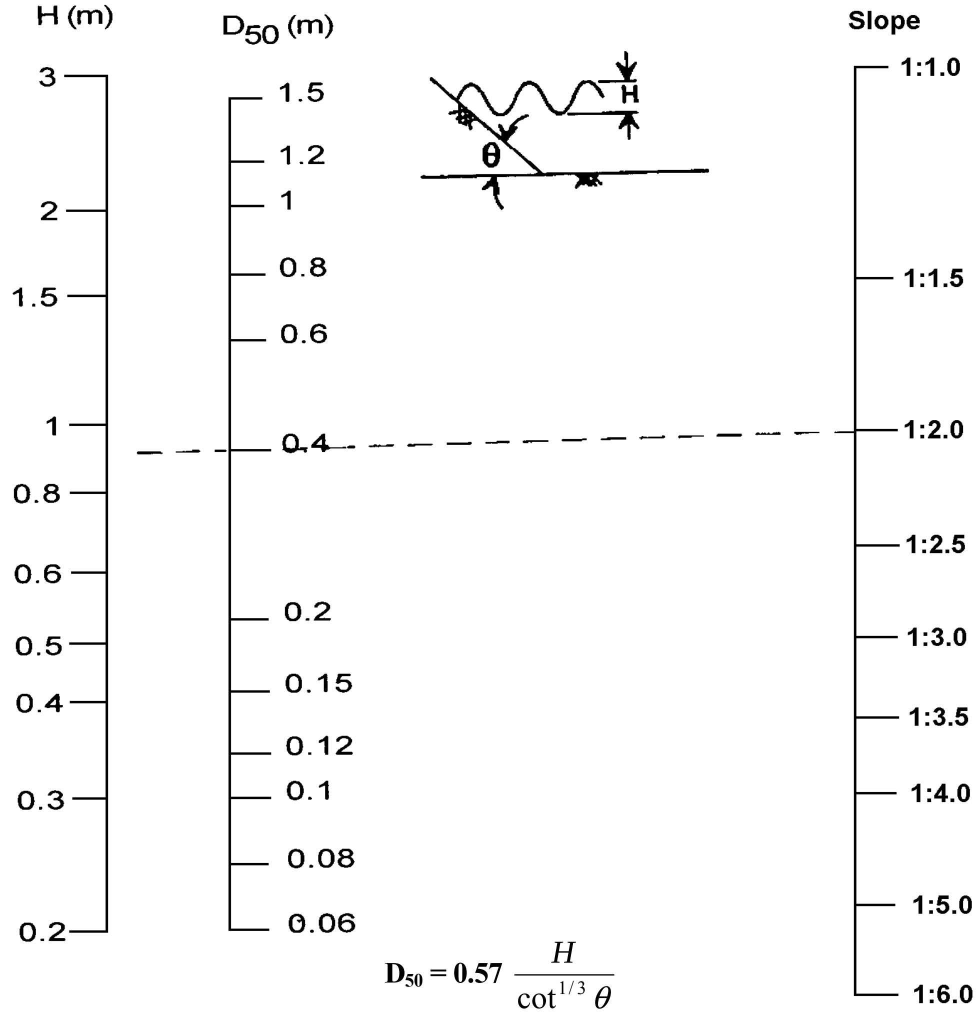
All stones should be contained reasonably well within the riprap layer thickness to provide maximum resistance against erosion. Oversize stones, even in isolated spots, may cause riprap failure by precluding mutual support between individual stones, providing large voids that expose filter and bedding materials, and creating excessive local turbulence that removes smaller stones. Small amounts of oversize stone should be removed individually and replaced with proper size stones. The following criteria apply to the riprap layer thickness.

1. It should not be less than the spherical diameter of the D_{100} stone, or less than 2.0 times the spherical diameter of the D_{50} stone, whichever results in the greater thickness.
2. It should not be less than 300 mm (12 in) for practical placement.
3. The thickness determined by either of the above criteria should be increased by 50% when the riprap is placed underwater to provide for uncertainties associated with this type of placement.
4. An increase in thickness, accompanied by an appropriate increase in stone sizes, should be provided where riprap revetment will be subject to attack by floating debris or ice, or by waves from boat wakes, wind, or bedforms.

The typical layer thickness for riprap (ConnDOT gradations) revetment is shown in Table 7-10.

Table 7-10 Riprap Layer Thickness

Riprap Type	Riprap Layer Thickness mm
Modified	300 (12 inches)
Intermediate	450 (18 inches)
Standard	900 (36 inches)



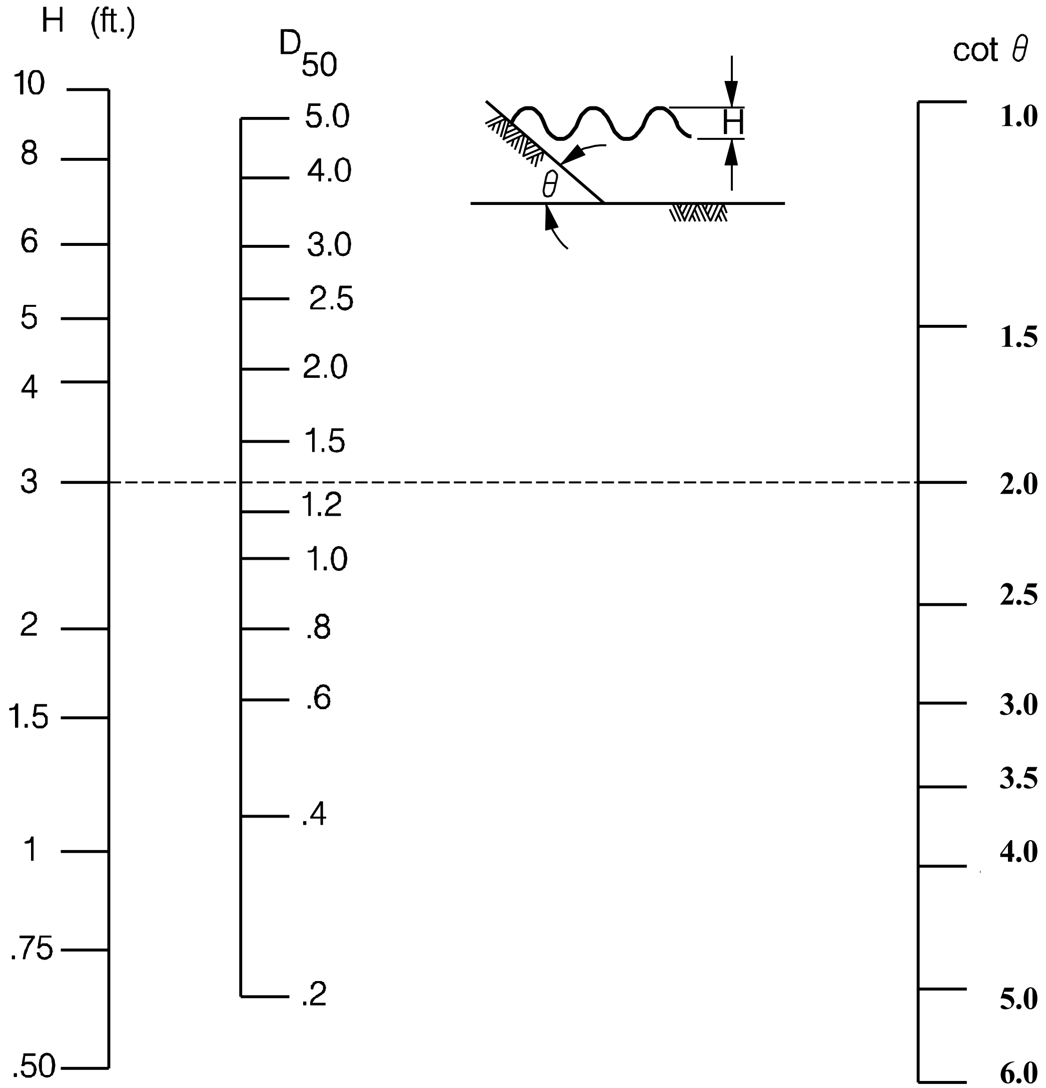
$$D_{50} = 0.57 \frac{H}{\cot^{1/3} \theta}$$

D_{50} = Median Riprap Size
H = Wave Height
θ = Bank Angle with Horizontal

Example

Given:	Find:	Solution:
Slope = 1V:2H	D_{50}	D_{50} = 0.4 m
H = 0.91 m		

Figure 7-29 Hudson Relationship For Riprap Size Required To Resist Wave Erosion – metric units



$$D_{50} = 0.57 \frac{H}{\cot^{1/3}\theta}$$

D_{50} = Median Riprap Size
H = Wave Height
θ = Bank Angle with Horizontal

Example:

Given:	Find:	Solution:
$\cot\theta = 2{:}1$	D_{50}	$D_{50} = 1.33$ ft.
H = 3 ft.		

Figure 7-29.1 Hudson Relationship For Riprap Size Required To Resist Wave Erosion – English units